

$\alpha_s(M_Z^2)$ and R_b discrepancy with nonuniversal interactionsJae Kwan Kim, Yeong Gyun Kim*, Jae Sik Lee[†] and Kang Young Lee[‡]*Department of Physics, KAIST, Taejeon 305-701, KOREA*

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Abstract

We implement global fits to LEP data with the nonuniversal interactions. Consistent R_b with experimental value and consistent $\alpha_s(M_Z^2)$ with that from low energy experiments are obtained. We also find that the χ^2 is better than the Standard Model. And we argue that other kinds of new physics are needed to explain the difference between the values of $\alpha_s(M_Z^2)$ from low energy experiments and from the 3-jet ratio.

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*ygkim@chep6.kaist.ac.kr

[†]jslee@chep6.kaist.ac.kr

[‡]kylee@chep5.kaist.ac.kr

Recently the Collider Detector of Fermilab (CDF) Collaboration presented evidence for a top quark with a mass $m_t \sim 175$ GeV [1]. Such a heavy top affects the partial width of $Z \rightarrow b\bar{b}$ and recent analysis indicates that the experimentally measured value for the ratio $R_b \equiv \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadron})$ is higher than the Standard Model (SM) prediction at a 2.5σ level [2,3]. This discrepancy may be the first signal for new physics beyond the SM if it will be confirmed by future experiments. A number of possible scenarios of new physics are being suggested to explain this R_b discrepancy.

The nonuniversal interaction acting on only the third generation attracts us as a candidate for the new physics since the SM predictions for other flavours should not be disrupted by the new physics. Models of this type are motivated by the idea that the top quark has a mass of the order of the weak scale and would play a key-role in electroweak symmetry breaking via top quark condensation [4]. Considering the general approach, the anomalous nonuniversal interaction terms are $SU(2)_L \times U(1)_Y$ invariant and the b -quark will take part in top quark interactions when the left-handed doublet is involved. This can result in a modification of the $Z \rightarrow b\bar{b}$ vertex. We parametrize the nonuniversal interaction effects in the $Z \rightarrow b\bar{b}$ vertex by introducing the parameters $\kappa_{L,R}$. These parameters shift the SM tree level couplings of the neutral currents $g_{L,R}$ to the effective couplings $g_{L,R}^{\text{eff}}$

$$g_{L,R}^{\text{eff}} = g_{L,R}(1 + \kappa_{L,R}) \quad (1)$$

where

$$g_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W, \quad g_R = \frac{1}{3} \sin^2 \theta_W \quad .$$

It was shown that R_b could be fitted to the LEP data within 1σ with nonuniversal interactions in the ref. [5].

Another possible deviation of the LEP/SLC data from the SM is being proposed. Shifman [6] has pointed out that the value of the strong coupling constant $\alpha_s(M_Z^2) \simeq 0.126$ determined by global fits to the Z -line shape variables at the Z -peak shows much discrepancy with $\alpha_s(M_Z^2) \simeq 0.112$ extracted from low energy experiments, which is scaled to M_Z

scale. And we note that the value of $\alpha_s(M_Z^2) \simeq 0.119$ from events shape variables also shows difference from that from low energy experiments. Kane et al. [7] noticed this point in relation to the R_b discrepancy. They reanalyzed the LEP/SLC data in minimal supersymmetric standard model (MSSM) scheme with light superpartners and found that the global fit with low $\alpha_s(M_Z^2) = 0.112$ yields better fit to the data than that of the SM. Several authors have noted that if R_b is explained by new physics, then in general $\alpha_s(M_Z^2)$ will decrease.

In this paper we study the model with nonuniversal interactions to explain the α_s problem and R_b discrepancy. We do not construct a specific model but use the effective lagrangian technique. We take the $Z \rightarrow b\bar{b}$ vertex to be given phenomenologically by the expression

$$\mathcal{L} \sim Z^\mu (\bar{b} \gamma_\mu (g_V^{\text{eff}} + g_A^{\text{eff}} \gamma_5) b) \quad (2)$$

where g_V^{eff} and g_A^{eff} are the effective vector and axial coupling constants given by

$$\begin{aligned} g_V^{\text{eff}} &= 2(g_R^{\text{eff}} + g_L^{\text{eff}}) \\ g_A^{\text{eff}} &= 2(g_R^{\text{eff}} - g_L^{\text{eff}}) \quad . \end{aligned} \quad (3)$$

We used ZFITTER [8] with the function minimizing program MINUIT [9] to perform the χ^2 fit for the LEP observables. By χ^2 fitting to the LEP observables with nonuniversal interactions, we find that the value of $\alpha_s(M_Z^2) = 0.103$ lies at the global χ^2 minimum.

Alternatively we consider the extraction of α_s from 3-jet ratio. We observe that this jet variable is very insensitive to the modification of the $Z \rightarrow b\bar{b}$ vertex given in eq. (1). So we find that this jet variable can be used to extract $\alpha_s(M_Z^2)$ independently of such kinds of new physics that effectively change g_L and g_R .

For completeness, we implement the χ^2 fit to the data in the SM framework at first. The SM value of $\alpha_s(M_Z^2)$ from the Z line shape variables has been reported to be $\alpha_s(M_Z^2) = 0.126 \pm 0.005$ by LEP Electroweak working group [3]. We use the set of following 12 variables in our fitting procedure [2]: M_W , Γ_Z , σ_{tot} , $R_l \equiv \Gamma_{had}/\Gamma_{lepton}$, A_{FB}^{lep} , A_τ , A_e , R_b , R_c , A_{FB}^b , A_{FB}^c , $\sin^2 \theta_W^{lep}$. The Higgs mass is fixed to be 100 GeV. Our χ^2 fit is not sensitive to the values of Higgs mass in the region $m_H = 100\text{--}1000$ GeV. As fitting parameters, we use t -quark mass m_t and α_s . We obtain followings:

$$m_t = 162.67 \pm 8.98 \text{ GeV}, \quad \alpha_s(M_Z^2) = 0.121 \pm 0.004 \quad .$$

These results are consistent with the fits obtained by the LEP Electroweak working group.

The deviation of Γ_b from the SM by the effects of $\kappa_{L,R}$ is expressed by

$$\frac{\delta\Gamma_b}{\Gamma_b} \sim 2 \frac{g_L^2 \kappa_L + g_R^2 \kappa_R}{g_L^2 + g_R^2} \quad . \quad (4)$$

Since $g_L^2 \gg g_R^2$, κ_R does not affect much on Γ_b and we can neglect the second term. Therefore we fix $\kappa_R = 0$ in our analysis.

With a nonzero parameter κ_L , we implement the χ^2 fit to the same set of LEP observables. We found the much better χ^2 than the SM, well-agreed R_b within 1σ range of experimentally measured value and the lower $\alpha_s(M_Z^2)$ than that of the SM. We obtain the values:

$$\begin{aligned} m_t &= 165.33 \pm 8.70 \text{ GeV} \quad , \\ \alpha_s(M_Z^2) &= 0.103 \pm 0.009 \quad , \\ \kappa_L &= 0.013 \pm 0.006 \quad . \end{aligned}$$

The results of our χ^2 fit to LEP observables are summarized in Table 1 compared with those of the SM. In Fig. 1, we plot R_b as a function of κ_L for these values of m_t and $\alpha_s(M_Z^2)$.

Because we take a model-independent approach, we do not explicitly describe the parameter κ_L by specific physical quantities here. We know, however, that κ_L is related to the new physics scale Λ . For example, if we take the relevant term of the effective lagrangian as the 4-fermion coupling

$$\mathcal{L}_{\text{eff}} \sim -\frac{1}{\Lambda^2} \bar{b} \gamma_\mu b \bar{t} \gamma^\mu (g_V + g_A \gamma_5) t \quad , \quad (5)$$

κ_L is computed by t -quark correction to the $Z \rightarrow b\bar{b}$ vertex as follows

$$\kappa_L = \frac{g_A}{g_L} \frac{N_c}{8\pi^2} \frac{m_t^2}{\Lambda^2} \ln \left(\frac{\Lambda^2}{m_t^2} \right) \quad . \quad (6)$$

Our fit result $\kappa_L \sim 0.013$ yields $\Lambda \sim 1.5 \text{ TeV}$ from eq. (6).

The value of $\alpha_s(M_Z^2)$ at the Z -peak can also be extracted from jet event shape variables. There are several jet variables; thrust, jet mass, energy-energy correlation, oblateness,

C-parameter, jet multiplicity and 3-jet ratio etc.. Here we explore the effects of the nonuniversal interactions on 3-jet ratio and determination of $\alpha_s(M_Z^2)$.

Jets are defined as a bunch of particles based on jet-clustering algorithms. For example, with a jet-clustering algorithm in the EM scheme [10], two particles are regarded as belonging to the same jet if their momenta satisfy the condition

$$y_c > y_{ij} = 2 \frac{p_i \cdot p_j}{s} \quad (7)$$

where \sqrt{s} is the total energy of collision and y_c , so-called y -cut, is a given resolution parameter.

We used the 3-jet decay width at the Z peak formula derived by Bilenky et al., which is calculated up to the order of α_s and $r_b \equiv m_b^2/m_Z^2$. Their analytic expressions are found in ref. [11]. We calculate the ratio of Γ_{3jet}^b to Γ_b with the nonuniversal interactions given in eq. (1) for the values of the parameter $\kappa_L=0, 0.02, 0.08$.

$$\begin{aligned} R_{3j} &= 0.2450 & \text{for } \kappa_L &= 0 \quad , \\ R_{3j} &= 0.2449 & \text{for } \kappa_L &= 0.02 \quad , \\ R_{3j} &= 0.2448 & \text{for } \kappa_L &= 0.08 \quad . \end{aligned} \quad (8)$$

We used $\alpha_s = 0.119$ which is reported by LEP Electroweak working group for event shape variables [3]. Each value of κ_L corresponds to the Standard Model, $\Lambda \sim 1$ TeV and $\Lambda \sim 300$ GeV if we assume the effective lagrangian such as eq. (5). The change of 3-jet ratio with varying κ_L is very slight and it cannot change the value of $\alpha_s(M_Z^2)$. We conclude that this variable is very insensitive to the change of the parameter κ_L and the value of $\alpha_s(M_Z^2)$ extracted from this variable is not lowered by introduction of the new physics effects such as eq. (1), contrary to the case of the line shape variables.

When one introduce the new physics beyond the SM to cure the R_b discrepancy, the value of $\alpha_s(M_Z^2)$ is usually known to be lower than that extracted from the SM. This fact can be the answer of the problem that the value of $\alpha_s(M_Z^2)$ emerging from the global fits on the data at the Z -peak is almost 3σ deviations higher than the value stemming from

the low energy phenomenology. With a generic nonuniversal correction given in eq. (1), we implemented the global fits to the observables of LEP and found that $\alpha_s(M_Z^2) \simeq 0.103$ gives the best fit. All the data including R_b are consistent with our model predictions.

We also found that the 3-jet ratio is very insensitive to this nonuniversal correction. If we predict this jet variable more exactly, therefore, we can extract $\alpha_s(M_Z^2)$ from the jet ratio independently of new physics as eq. (1). If an exact determination of $\alpha_s(M_Z^2)$ from the jet ratio still shows discrepancy with α_s from low energy value, it may mean the existence of other kinds of new physics different from that described by eq. (1).

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TABLES

TABLE I. Our global fit results to LEP observables in the Standard Model framework and with the nonuniversal interactions.

FIGURES

FIG. 1. Plot of R_b as a function of the parameter κ_L . The solid line denotes the prediction with nonzero κ_L and the dashed line the Standard Model prediction. The hatched area represents the LEP data within 1σ error.

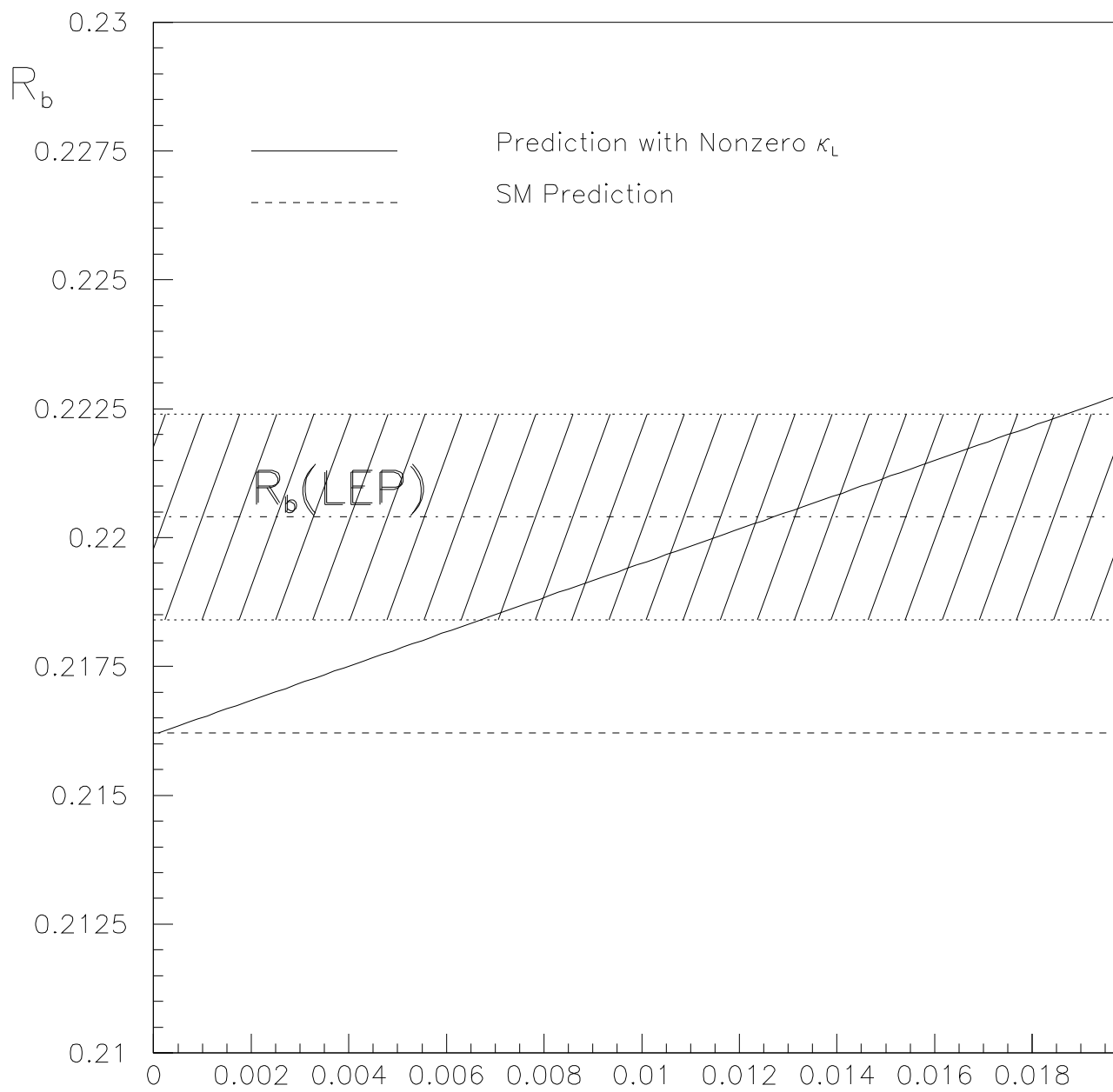


Fig. 1

κ_L

Observables	Experiment	SM results	χ^2	New Physics	χ^2
$M_W(\text{GeV})$	80.33 ± 0.18	80.3225	0.002	80.3393	0.003
$\Gamma_Z(\text{GeV})$	2.4971 ± 0.0033	2.4971	0.000	2.4976	0.023
$\sigma_{tot}(\text{nb})$	41.492 ± 0.081	41.396	1.397	41.399	1.321
R_l	20.815 ± 0.033	20.801	0.184	20.799	0.247
A_{FB}^{lep}	0.0172 ± 0.0013	0.0155	1.628	0.0157	1.337
A_τ	0.140 ± 0.008	0.144	0.244	0.145	0.341
A_e	0.137 ± 0.009	0.144	0.596	0.145	0.726
R_b	0.2204 ± 0.0020	0.2161	4.536	0.2205	0.002
R_c	0.1606 ± 0.0095	0.1710	1.189	0.1700	0.983
A_{FB}^b	0.1015 ± 0.0036	0.1010	0.019	0.1017	0.003
A_{FB}^c	0.0760 ± 0.0089	0.0720	0.206	0.7214	0.168
$\sin^2 \theta_W^{lep}$	0.2320 ± 0.0016	0.2320	0.000	0.2319	0.003
total			10.0		5.2

Table 1: